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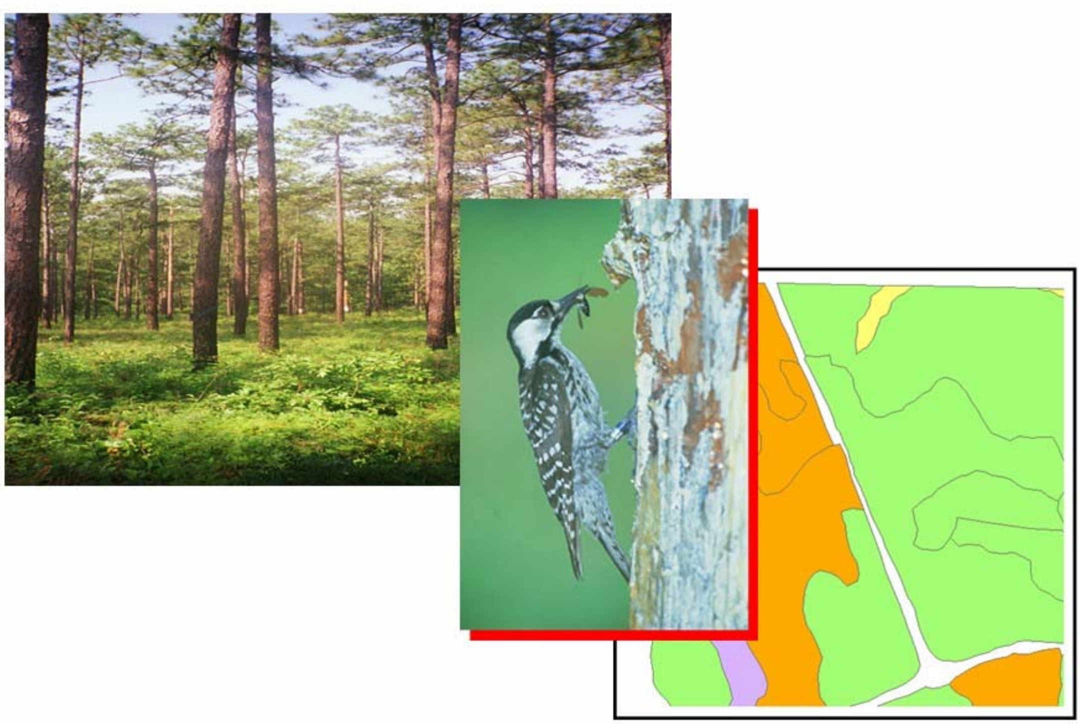
Remote Sensing for Threatened and Endangered Species Habitat Assessment on Military Lands

A Literature Review

Scott A. Tweddale and Robert H. Melton

April 2005



Construction Engineering
Research Laboratory

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Remote Sensing for Threatened and Endangered Species Habitat Assessment on Military Lands

A Literature Review

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Final Report

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ABSTRACT: The presence of federally listed threatened and endangered species (TES) and their habitats on Department of Defense (DoD) lands has a significant impact on current and future training and testing mission activities. To meet the requirements of the Endangered Species Act, the DoD requires accurate, cost-effective surveying and monitoring methods to characterize and monitor the habitats of TES on military training and testing lands.

Remotely sensed imagery provides an ideal supplement, or surrogate, to field surveys and has the potential to greatly enhance the speed, accuracy, and economy of TES habitat assessments. This report provides a general overview of relevant literature describing the best available science and protocols currently implemented to characterize and monitor habitat for TES, with a particular emphasis on the seven high priority species of the DoD: Indiana bat (*Myotis sodalis*), gray bat (*Myotis grisescens*), gopher tortoise (*Gopherus polyphemus*), desert tortoise (*Gopherus agassizii*), red-cockaded woodpecker (*Picoides borealis*), black-capped vireo (*Vireo atricapillus*), and the golden-cheeked warbler (*Dendroica chrysoparia*).

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Contents

Conversion Factors

Non-SI* units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

*_Système International d'Unités_ ("International System of Measurement"), commonly known as the "metric system."

Preface

This study was conducted for the Office of the Director of Environmental Programs under A896, “Base Facility Environmental Quality”; 5H1893, “Remote Sensing for TES.” The technical monitors were Vic Diersing and Bill Woodson, DAIM-ED-N.

The work was performed by the Ecological Processes Branch (CN-N) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Scott A. Tweddale. The authors would like to acknowledge Matthew G. Hohmann (CN-N) for his review of select topics in this report. The technical editor was Gloria J. Wienke, Information Technology Laboratory. Steve Hodapp was Chief, CEERD-CN-N at the time of this research. Dr. John T. Bandy is Chief, CEERD-CN. The associated Technical Director is Dr. William D. Severinghaus, CEERD-CV-T. The Director of CERL is Dr. Alan W. Moore.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL James R. Rowan, and the Director of ERDC is Dr. James R. Houston.

1 Introduction

Background

The presence of federally listed threatened and endangered species (TES) and their habitats on Department of Defense (DoD) lands has a significant impact on current and future training and testing mission activities. Implementation of the Endangered Species Act has resulted in constraints on the location, time, access, and intensity of training activity and continues to result in reduced training capacity of military lands. Proposed listings for additional species, increased land requirements to support future combat systems (lighter, mobile, unmanned) and other training doctrinal changes, and habitat loss due to urban encroachment in the vicinity of many installations suggest that these constraints will accelerate if they are not addressed. Seven TES species are presently considered the most important and most likely to impact Army training in the near future. These species are the Indiana bat (*Myotis sodalis*), gray bat (*Myotis grisescens*), gopher tortoise (*Gopherus polyphemus*), desert tortoise (*Gopherus agassizii*), red-cockaded woodpecker (*Picoides borealis*), black-capped vireo (*Vireo atricapillus*), and the golden-cheeked warbler (*Dendroica chrysoparia*). To meet the requirements of the Endangered Species Act, the DoD requires accurate, cost-effective surveying and monitoring methods to characterize and monitor the habitats of these and other TES that exist on military training and testing lands.

Traditional ground-based and labor-intensive field inventory and monitoring protocols for characterizing and monitoring TES habitats across DoD installations are cost-prohibitive, particularly if repeated surveys are required for monitoring. Remotely sensed imagery, because of its large geographic coverage and high temporal frequency, provides an ideal supplement, or surrogate, to costly field surveys. In addition, because imagery provides a complete census of the landscape, it is possible to assess areas that are otherwise inaccessible to field surveys (e.g., impact areas, adjoining private land). Remote sensing is a technology of increasing importance in wildlife habitat studies, and when remotely sensed data is combined with other spatially explicit data using geospatial technologies, it has the potential to greatly enhance the speed, accuracy, and economy of TES habitat assessments.

The DoD and many other federal, state, and private land owners have investigated and implemented a wide variety of TES inventory and monitoring programs that use a combination of field surveys and remotely sensed imagery. Although advances have been made with respect to certain TES and their preferred habitats, significant information gaps still exist. Many TES monitoring protocols are still inefficient and lack the accuracy required by regulators. As a result, standard protocols to inventory and monitor TES habitats across large geographic areas are lacking. The information gaps are sometimes due to a lack of understanding of basic habitat requirements for some species. In other cases, the basic habitat requirements of a species are well understood, but information gaps exist because field monitoring protocols are cost-prohibitive and because of the inability of remote sensing technologies to discriminate critical parameters that define viable habitat. Significant resources have been expended to develop inventory and monitoring programs that incorporate remote sensing protocols and geospatial technologies for federal, state, and private land owners. As a result, a vast amount of literature exists on these topics. Most of the literature spans a period from the late 1970's to present, which corresponds to the time period that commercially available satellite imagery has been available to the research community. During this time period, most of the literature focused on the use of passive spectral systems (e.g., Landsat Multispectral Scanner [MSS] and Thematic Mapper [TM] and SPOT imagery) with relatively limited spatial resolution (20 to 80 m) for monitoring TES habitat. With the emergence of high spatial and spectral resolution, active and passive sensors, results in the literature suggest that these systems may be able to address critical information gaps in TES habitat monitoring, such as sensing of sub-canopy components of forests and woodlands or improved ability to determine species composition.

To address these information gaps, the U.S. Army Engineer Research and Development Center-Construction Engineering Research Laboratory (ERDC-CERL) has initiated a research project titled "Remote Sensing for Threatened and Endangered Species (TES)". The objective of the project is to develop and refine cost-effective and accurate protocols and techniques to identify and monitor viable habitat for TES from a combination of field surveys and remotely sensed imagery, allowing for interpretations of large and inaccessible areas. Specifically, the objective is to investigate the utility of rapidly advancing remote sensing technology that may help overcome limitations of traditional sensors, and develop inventory and monitoring protocols that not only address habitat characterization and monitoring requirements for the seven high priority species listed above, but also are adaptable to other species as they become critical to management of DoD lands.

This document provides a general overview of relevant literature describing the best available science and protocols currently implemented to characterize and monitor habitat for TES, with a particular emphasis on the seven high priority species of the DoD.

Objectives

The first objective of this research is to review techniques and protocols for the application of geospatial technologies, with an emphasis on remote sensing technologies, for use in discrimination, assessment, and monitoring of TES habitats. Based on this review, a second objective is to identify the current limitations and information gaps of such protocols, and in particular, those information gaps or limitations that could potentially be addressed with emerging sensor technology to assess TES habitats on Army installations.

Approach

A comprehensive review of scientific literature related to the characterization and monitoring of TES habitats using remote sensing was completed. As part of the overview, the challenges associated with characterizing TES habitats, including an explanation of relevant terminology and concepts, are provided.

Scope

This review is limited to the application of geospatial technologies for characterizing and monitoring the habitats of fauna, with an emphasis on the habitats of seven species that are high priority to the DoD. In some cases, a specific habitat requirement may be common to multiple species, and therefore, the methods to characterize that individual habitat requirement may be applicable and adaptable to other species. An exhaustive review of basic techniques of remote sensing or a complete review of habitat studies, which draws upon scientific knowledge from a broad and diverse set of scientific disciplines, is beyond the scope of this report. This review does not address remote sensing techniques for directly monitoring the movements and behavior of fauna, nor does it specifically address remote sensing technique for characterizing threatened and endangered flora. However, some techniques to characterize flora for the purpose of characterizing habitats of fauna may indeed be applicable to endangered flora.

Mode of Technology Transfer

Information from this study will be disseminated as an ERDC/CERL report to military personnel and other interested parties. The report will also be made accessible through the World Wide Web at: http://www.cecer.army.mil

2 Review of the Methods

Terminology

There has historically been considerable ambiguity in the use of the word “habitat” (Corsi et al. 2000). The term has been used, often interchangeably, as an attribute of land and as an attribute of a species. In the former sense, it is a generic term for a spatially defined geographic unit that is relatively homogeneous with respect to vegetation and environmental structure. In this sense, all land is habitat of some sort, and under this usage landcover maps are often referred to in the literature as “habitat maps.” In the second sense, “habitat” refers to the environment in which a particular species lives, and is only meaningful in relation to a given species.

The term “habitat” will, in this document, be used in the second sense: the term will be used only in connection with a species, as in “black capped vireo habitat”. However, even under this species-centered definition, the concept of habitat is not an all-or-nothing proposition. For example, the distinction between black-capped vireo (BCV) and golden-cheeked warbler (GCW) habitats is not mutually exclusive. Rather, there exists a considerable degree of inter-gradation between the two species’ habitats, and between habitat and non-habitat areas as well. Over time, the suitability of a piece of land may be increasing for one species while decreasing for another. Thus a species’ habitat can be usefully thought of as fuzzy set, as defined by Zadeh (1965). Under this definition, habitat is a species-specific fuzzy set, which allows for varying degrees of truth (degrees of “is habitat”), defined between 0 (fully “false”) and 1 (fully “true”) among different patches of land. This conception is consistent with the 0-to-1 continuum “habitat suitability index” advocated by the U.S. Fish and Wildlife Service (1981). A benefit that accrues from treating habitats as fuzzy sets is that this allows the potential for analyses using fuzzy logic. An excellent introductory text on the uses of fuzzy logic is by Ross (1995), who provides clear and practical expositions on the classical and fuzzy counterparts of logic.

The concept of habitat is related to, and ultimately derives from, the concept of the species “niche.” The prevailing niche concept presented in standard ecological textbooks (e.g., Begon et al. 1990) is attributed to Hutchinson (1957). This concept states that organisms of a given species can grow, survive, and reproduce most optimally within a certain range of values on any given single ecological variable. These variables are usually conceived as continuous or ordinal (e.g., temperature, salinity, humidity). They may conceivably also be nominal or "class" variables (e.g., species of tree used as nest substrate), although such ostensibly nominal classes may sometimes represent discontinuities in, or interaction effects among, one or more continuous variables related to that class (e.g., degree of shelter from direct solar radiation, or obscurance of the nest from predators, provided by that tree species). Each species exhibits variation in "fitness" (essentially a function of growth, survival, and reproductive rates) over a range of values on each ecological variable. If it is assumed (for simplicity) that this function is Gaussian, then the fitness of a species on a given ecological variable would look like the classic bell-shaped curve, a function having a maximum fitness (normalized to a value of 1) at a specific value on that axis, with progressively decreasing fitness, and declining "population viability," to either side of this optimum. A species niche can be conceived of as the total combination of such functions, along with their interactions or correlations, on many (say "N") ecological variables; i.e., as an "N-dimensional hypervolume," the term "dimension" being used in the multivariate statistical sense.

Therefore, a species habitat can be thought of as this N-dimensional hypervolume as it is realized by a species population in 3-dimensional Euclidean space, or (on a map) as a 2-dimensional projection thereof. While spatial delineation of habitats is the focus of this report, time is also an important dimension of the species niche. Habitats can, and do, change over time due to seasonal effects, ecological succession, and stochastic events (Kruse and Porter 1994; De Angelis et al. 1998; Stoms et al. 1992).

There is an important distinction between a species' "fundamental niche" and its "realized niche." In Hutchinson's conception, a species' fundamental niche is the N-dimensional hypervolume in which the population is viable in the absence of the effects of competitor species, predator species, or parasites. Pulliam (2000) expands the list of factors to include niche width, habitat availability, and dispersal. The species realized niche is the (reduced) N-dimensional hypervolume occupied by the species in the presence of these population-limiting factors. The fundamental niche may never be observed in its totality, although parts of it can be revealed if an important limiting factor is removed. A species distribution observed in nature generally will not reflect every environment in which it could possibly live based on physical conditions. They will, to some extent, be absent from suitable habitat and present in unsuitable habitat. Analysis of remotely sensed imagery alone for the purpose of delineating the spatial extent of habitat is well-suited to delineating the fundamental, rather than the realized niche for a given species. However, the exception would be in cases where the population-limiting factors themselves can be characterized with remotely sensed imagery. Conversely, a predictive habitat model based purely on observed patterns of a species distribution will reflect the realized, not the fundamental, niche.

In the present context of TES management, limiting factors include humans and their activities, which can be both beneficial and deleterious to species and their habitat. Using the intensive cowbird removal program at Fort Hood, TX, as an example, the subsequent increase in BCV numbers after the ensuing release from intense nest parasitism is a particularly relevant example of human activities that expand the range of potential suitable BCV habitats on the installation (Eckrich et al. 1999; Hayden et al. 2000). Training activities are potentially deleterious to TES. However, on the larger scale, military installations as a whole provide relative protection of suitable landcovers from private sector development, which has greatly reduced suitable habitats outside the installation boundary (Tazik and Martin 2002).

Typology of Predictive Habitat Models

Remote sensing provides a valuable tool for characterizing key physical and biological parameters of habitats, especially across large and sometimes inaccessible areas. However, data extracted from remotely sensed imagery alone is generally insufficient for delineating preferred or potential habitat for a species, as there are typically additional habitat parameters that cannot be observed from remote imagery. Instead, data extracted from remotely sensed imagery is typically combined with ancillary data and used as input to predictive habitat suitability models.

Numerous modeling techniques have been applied for the purpose of assessing habitat suitability. In addition, there are a large number of landscape indices that have been developed to quantify spatial patterns of the landscape that are critical to evaluating suitability of habitat. A complete review of such models and indices is beyond the scope of this report. However, a brief, general description of the types of models that are typically employed to predict habitat is provided below, based on discussions in the following references: Breiman 2001; Corsi et al. 2000a; de Leew et al. 2002; Gahegan 2003; Guisan and Zimmermann 2000; Hastie et al. 2001; Skidmore 2002; Woodcock et al. 2002. A more specific description of the application of such models to specific species, and to a limited extend, to species of concern to DoD, is provided in Chapter 3.

Selection of an appropriate predictive model depends on a number of variables, including the *a priori* knowledge or assumptions of a species preferred habitat and the key physical and biological parameters that describe that habitat; the spatial and temporal scale of the analysis; and the availability, validity, and accuracy of data related to the species (Guisan and Zimmermann 2000; Anderson et al. 2003).

Deductive vs. inductive habitat modeling

Two approaches are commonly followed to model the spatial distribution of habitat for species and assess habitat suitability using geospatial technologies: deductive and inductive. A deductive model draws a specific conclusion or prediction from a set of general propositions, or premises. Deductive models are commonly referred to as "knowledge-driven" or "process-driven" models. Validity of the model rests on the assumption that the conclusion necessarily follows from the premises, and in general the premises are more-or-less well-understood facts or observations about nature. Using a deductive approach, criteria that define suitable habitat are developed from existing knowledge of habitat requirements, and GIS and remote sensing are used to identify locations that meet such criteria.

Conversely, an inductive model uses a series of observed evidential facts to derive or prove a general proposition or pattern. The observed relationship between the evidential facts and the conclusion, even if strong and reliable, may not be well-understood, and, in very complex cases, may not even be understandable in principle. Using an inductive approach, habitat requirements are determined directly from empirical research by relating species presence/absence, or species "fitness" data at given locations, with biophysical characteristics of the locations. These approaches are not always mutually exclusive, as often the existing knowledge of habitat requirements used to define habitat criteria in a deductive approach is ultimately the result of previous inductive, empirical research.

Remote Sensing of Habitats

Remotely sensed data can be analyzed to map discrete categories or variables, or it can be used to estimate continuous variables. The process by which discrete variables are identified and delineated within an image is referred to as image segmentation or image classification. Spatially explicit estimates of continuous variables are typically developed through empirical modeling.

The process of predicting a species habitat (or, as it is widely referred to in the literature, modeling "habitat suitability") using remotely sensed imagery requires analysis and interpretation of data collected by active and passive remote sensing platforms. Image analysis and interpretation produces spatially explicit geographic information system (GIS) layers representing ecologically meaningful features of the landscape that are relevant to the habitat for a particular species. Geospatial data layers derived from remote observations are generally combined with other existing geospatial data, including spatial data representing the performance of a species on the landscape, to parameterize habitat suitability models. Spatial data representing the performance of a species on the landscape is also used to validate habitat suitability models (Corsi et al. 2000; de Leew et al. 2002; Farina 1998a,b; Quattrochi and Pelletier 1991; Woodcock et al. 2002).

The goal of the image analysis and interpretation process is generally to develop either a geospatial surface representing a continuous variable or a thematic data layer that delineates discrete categories. This report will not be an exhaustive review of basic image analysis and interpretation, as those subjects are covered extensively in standard remote sensing textbooks. However, a brief description of the process for developing thematic maps and mapping continuous variables from remotely sensed imagery is provided in the following section.

Thematic mapping

Airborne and spaceborne active sensors record reflectance in one (panchromatic) or multiple (multispectral) bands of various wavelengths. Each unique component of the ground surface, such as vegetation, soil, or a man-made surface, exhibits different reflectance characteristics in each of the spectral bands recorded by a sensor. Development of a thematic data layer requires the use of pattern recognition or image segmentation algorithms to analyze such spectral information. An image segmentation algorithm, often referred to as an image classification, is used to assign individual data elements or pixels within an image to discrete spectral categories based on their spectral properties. Reflectance values for some or all spectral bands recorded by the sensor for each individual pixel are considered in the segmentation process. Image classifications are commonly used to map several or all distinct landcover categories present in the image footprint. A number of different spectral classification algorithms can be used to conduct an image classification. Typically, classification is performed using either a supervised or an unsupervised method of training.

Supervised learning uses a set of predictor variables to estimate the values of one or more dependent outcome variables. The process is based on a "training" sample of previously solved cases, where the joint values of all the variables are known *a priori*. In a remote sensing context, the set of predictor variables in a remotely sensed image is the spectral information recorded by the remote sensor in one or more wavelengths, although ancillary data is often combined with spectral information as additional predictor variables. Using a supervised method, for each unique category that is to be mapped, the area where that category is known to exist (i.e., "ground truth") is located in the field or visually delineated on a digital image. These areas of ground truth serve as training samples for purpose of developing a spectral signature for each category that will be identified in the classification process. The spectral signature for each category must be spectrally homogenous, and should be spectrally unique from training samples for all other categories. Due to these requirements, it is difficult to use a supervised training approach to directly map potential habitat. A species habitat rarely exhibits a unique spectral signature. As described above, a species habitat or niche can be described as an N-dimensional hypervolume of ecological variables. Some of those ecological variables may influence the spectral response as observed by a remote sensing platform, but other variables may not. For example, the boundary of active red-cockaded woodpecker (RCW) clusters may be identified in the field, but it would be unreasonable to use these boundaries as training polygons to identify a spectral signature for "RCW habitat." The spectral signature might be affected by the botanical composition of the upper forest canopy within these boundaries, but other key components of habitat, such as the presence of midstory hardwood or preferred groundcover, would not significantly affect the spectral signature. As a result, if the spectral signature was used to identify other spectrally similar areas within the image using a supervised approach, it would delineate areas of similar forest canopy botanical composition, for example, but not necessarily other areas of RCW habitat. In addition, there is usually a considerable degree of inter-gradation between habitat and non-habitat rather than a discrete boundary, which makes it difficult, if not impossible, to accurately delineate training polygons.

Unsupervised learning uses an observed set of random variables with a joint probability density structure, and which are not differentiated into predictor and outcome variables. The properties of this joint probability density are directly inferred from the data without the help of a supervisor providing correct answers for each observation. Typically, in pattern recognition or remote sensing applications, these properties are then subsequently used to produce a classification for an image, but the resulting spectral classes are emergent properties of the process, and not known *a priori*. They are, however, subject to critical assessment and modification (or rejection) by the user *a posteriori*. Typically, after an unsupervised classification, the image analyst attempts to identify and assign category labels to the different spectral classes resulting from an unsupervised classification. In the context of mapping species habitats, the image analyst would identify those spectral classes that correspond to known habitat. Some categories may be merged if it is determined that they represent the same habitat. Ancillary data layers such as elevation and slope are often referenced for additional clues when assigning category labels. It is common to visit the field or rely on knowledge of the landscape to validate image classifications, and typically an iterative process is used whereby information gathered in the field is used to refine the classification. A combination of supervised and unsupervised techniques is often used to help improve the accuracy of the classification. However, the same limitations that apply to using a supervised classification for the purpose of delineating habitat for a species (i.e., habitats do not exhibit unique signatures) also apply to an unsupervised image classification for the same purpose.

Therefore, it is difficult, if not impossible to delineate a habitat for a species using only an unsupervised image classification.

Supervised and unsupervised image classifications are typically used to map the spatial location and extent of an individual variable within the N-dimensional set of variables that describe habitat rather than attempting to map preferred habitat directly. There are generally well-recognized relationships between vegetation, soils, and the habitat preference for many species. Therefore, remotely sensed imagery is analyzed to develop a spatially explicit thematic map of one or more of these N-dimensional sets of variables that determine habitat suitability. A complete overview of thematic mapping of such parameters is beyond the scope of this report. However, numerous references are available that describe scientifically sound methods for creating thematic maps of vegetation (Anderson et al. 1972; Kessel 1979; Kuchler and Zonneveld 1988; Lachowski and Golden 1995; O'Neil and Hill 2000). Numerous references are also available for creating soils maps (Condit 1972; Stoner and Baumgardner 1981; Palacios-Orueta and Ustin 1996; Ahn et al. 1999; Zhu et al. 2001) and many other thematic data layers at multiple scales. These thematic maps can then be used as spatially explicit, independent variables in habitat suitability models.

Continuous variable mapping

In addition to thematic information that is extracted from remotely sensed imagery to support habitat suitability modeling, remotely sensed data is also commonly analyzed and interpreted to produce a spatially explicit estimate of continuous variables that may be critical to assessing habitat suitability. For any given continuous variable, field measurements of that variable (the dependent variable) are correlated with spectral data or information derived from spectral information (the independent variable) at the same location as the field measurements to parameterize a spatially explicit model. Using this model, estimates of the dependent variable are then assigned to each pixel in the image and spatially extrapolated across the geographic extent of the image using a GIS.

A large number of ecological parameters that are critical for evaluating habitat suitability have been derived from remotely sensed imagery in this manner, including, but not limited to soil organic matter (Sudduth and Hummel 1991), soil nitrates (Hummel and Birrell 1995), soil conductivity (Kitchen et al. 1996), total vegetative biomass and percent cover (Kauth and Thomas 1976; Tucker 1979; Curran 1980; Huete 1988; Qi et al. 1994; Tweddale et al. 2001), erosion protection (Price 1993; De Jong 1994; Senseman et al. 1996; Tweddale et al. 2000), soil moisture (Avery and Haines-Young 1990), biodiversity (Nagendra 2001), vegetation canopy height (Harding et al. 2001; Hudak et al. 2002; Leyva et al. 2002; Mason et al. 2003) and vegetation structure (Franklin and McDermid 1993; Lefsky et al. 1999b; Drake et al. 2002; Leyva et al. 2002).

Habitat Suitability Modeling with Geospatial Technologies

Thematic or continuous data derived from remotely sensed imagery are rarely analyzed independently to assess habitat suitability. Instead, such information is commonly combined with additional ancillary data deemed necessary, as independent input variables, to predict one or more dependent (outcome) variables representing the local fitness in geographic space (presence or absence and, if possible, survival and/or reproduction) of a species on the landscape. The use of a GIS facilitates the analysis of multiple, spatially explicit data layers from a variety of sources and at varying scales. Ancillary data used as inputs may include GIS layers such as a digital elevation model (DEM), existing thematic maps such as soils or geology, locations of salient geographical features such as roads or rivers, and previously known qualities of the species' habitat (Ormsby and Lunetta 1987; Hodgson et al. 1988; Palmeirim 1988; Shaw and Atkinson 1990; Congalton et al. 1993; Debinski et al. 1999; Hansen et al. 2001; Roy et al. 1995; Austin et al. 1996; Hepinstall et al. 1996; Porwal et al. 1996; Ozesmi and Mitsch 1997; Verlinden and Masogo 1997; Kracker 1999; Tobalske and Tobalske 1999; Lenton et al. 2000; Puestow et al. 2001; de Leew et al. 2002; Lauver et al. 2002; Luoto et al. 2002; Reunanen et al. 2002; Skidmore 2002). The process of training a species' fitness or density on geography using GIS is typically referred to as traditional habitat suitability modeling, and by its very nature is an exercise in supervised learning (Hastie et al. 2001). The process of analyzing each of the N-dimensional variables that describe habitat in a spatially explicit manner allows habitat suitability to be characterized as a continuous variable across the landscape, with gradients of suitability rather than as discrete classes of suitable and unsuitable habitat. The importance of each of the N-dimensional variables that describe habitat can be weighted accordingly in the analysis. The guidelines provided for habitat suitability modeling provided by the U.S. Fish and Wildlife Service (1981) more narrowly specify the outcome variable as a habitat suitability index (HSI), which must vary between values of 0 and 1, and optimally be proportional to the carrying capacity of the local habitat for the species.

In addition to the traditional, deductive methods of modeling habitat suitability with multiple data layers in a GIS, numerous alternative, inductive modeling approaches have been developed for the purpose of assessing habitat suitability (Guisan and Zimmermann 2000). Some of the most common types of modeling approaches involve relating species presence/absence or density to various habitat parameters using regression (Morrison et al. 1987; Pereira and Itami 1991; Carroll et al. 1999; Griffiths et al. 1999; Corsi et al. 2000; Franco et al. 2000; Reich et al.

2000; Manel et al. 2001; Osborne et al. 2001; Cross and Peterson 2001), multivariate analysis (Livingston et al. 1990; Robinson et al. 1997; Knick and Dyer 1997; Jaberg and Guisan 2001; Horne and Anders 2001), geostatistics (Estrada-Pena 1988), regression and classification tree modeling (Anderson et al. 2000; Debeljak et al. 2001), Bayesian predictive modeling (Aspinall and Veitch 1993; Hepinstall and Sader 1997; Tucker et al 1997) and fuzzy rules (Rickel et al. 1998; Kampichler et al. 2000). Remotely sensed data is integral to such modeling approaches because it provides a complete and rigorous sample of the landscape, including otherwise inaccessible areas.

A review of habitat suitability modeling would be incomplete without mentioning the large number of landscape pattern indices that have evolved from the science of landscape ecology. Such indices have been developed to quantify spatial patterns in the landscape and are commonly used to assess habitats at regional or landscape scales and characterize and monitor connectivity, edge effects, patch size, heterogeneity or fragmentation of habitats (Farina 1988; Turner 1989; Haines-Young et al. 1993; Gustafson 1998; Dove 2001; Turner et al. 2001; Patil et al. 2001; Lawler and Edwards 2002; Perry et al. 2002). An overview of many spatial statistics and indices that have been developed and are commonly used in ecological studies, with references to several spatial statistical computer programs, is given in Legendre and Legendre (1998).

3 Remote Sensing for Habitat Assessment on Military Lands

Management of threatened and endangered species on Army installations is a task with substantial economic and logistic consequences for the military training mission. In order to comply with the Endangered Species Act, the Army has mandated, under Army Regulation (AR) 200-3, an ongoing commitment to the preservation and management of TES on its installations, in conjunction with the U.S. Fish and Wildlife Service and other federal agencies. An important aspect of this mandate is the optimal management of habitats that support TES, while maintaining the primary installation mission of sustainable training and combat readiness. Thus, reliable methods for discerning TES habitats, and estimation of their potential carrying capacity for populations of TES, are important to both the conservation and training missions at DoD installations. Habitat characterization and monitoring protocols are required to determine the spatial extent and condition of potential habitat to determine how many individual TES it can likely support, both presently and in the future. This information, in turn, is used to determine what, if any, restrictions on military activities are required to assure reasonable compliance with the Endangered Species Act.

Seven TES species are presently considered the most important and most likely to impact Army training in the near future. These species are the Indiana bat (*Myotis sodalis*), gray bat (*Myotis grisescens*), gopher tortoise (*Gopherus polyphemus*), desert tortoise (*Gopherus agassizii*), red-cockaded woodpecker (*Picoides borealis*), black-capped vireo (*Vireo atricapillus*) and the golden-cheeked warbler (*Dendroica chrysoparia*). Remote sensing is critical to habitat characterization efforts because field sampling methods are cost-prohibitive for large geographic areas, and some areas, such as impact areas and private lands adjoining installations, are inaccessible. Remote sensing is even more critical to monitoring efforts, because TES habitats are dynamic, both in terms of extent and condition, due to anthropogenic stressors, including military training impacts, and natural successional processes.

One of the primary reasons that the TES listed above are of critical concern to the DoD is that they exist at multiple installations. Most installations where these species are found are using geospatial technologies as part of their TES characterization and monitoring activities, although the use of such technology varies in level of complexity, and also varies by species, installation, and ecoregion. In some cases, GIS is used primarily to archive, display, and communicate spatially explicit information related to management of habitats. In other cases, geospatial analysis and modeling techniques are used as a decisions support tool that is relied upon to make informed land management decisions related to management of habitats.

Similarly, remote sensing is used in various different ways and at varying levels of complexity to assess TES habitats, and also varies by species, installation, and ecoregion. Analysis of aerial photography and imagery is commonly used to assess the landscape and to characterize natural resources of DoD installations. In many cases, a vegetation map of installations has been developed through a combination of field surveys and analysis of airborne and satellite imagery. Moderate resolution imagery (20 to 30m) can be used to develop a general physiognomic (life form) vegetation map that might differentiate between forest, shrublands, and grasslands, for example. Interpretation of larger scale and higher spatial resolution color and color infrared photography may produce a physiognomic subclass map that differentiates evergreen from deciduous, for example, or may categorize forested stands according to general descriptions of canopy closure (e.g., high, medium, low) (O'Neil and Hill 2000). Such vegetation maps often provide a baseline inventory and a very general depiction of the location, and sometimes condition of habitats for certain species. Traditional photography and imagery has also been used to characterize more detailed and specific biophysical parameters that are critical for determining habitat suitability, including soil classifications, total vegetative cover and forest stand age, and other forest biophysical parameters.

This chapter does not summarize the various remote sensing protocols that are implemented at each installation where they are found. Instead, this chapter briefly describes the preferred habitat characteristics for each of the identified species, and more importantly, identifies specific habitat requirements where information gaps exist and identifies emerging remotely sensed data sources and associated analysis techniques that may potentially address these gaps.

Black-capped Vireo and Golden-cheeked Warbler

Background

Although the black-capped vireo and the golden-cheeked warbler have different habitat requirements, their habitats are commonly inter-mixed, and therefore are discussed jointly rather than separately. They are both small, insectivorous, migratory songbirds native to central Texas. The historical ranges, general characteristics, and ecology of these federally endangered species have been summarized both in their respective recovery plans and elsewhere (Campbell 1995; Grzybowski 1995;

Ladd and Gass 1999; U.S. Fish and Wildlife Service 1991, 1992). Both species have been managed intensively on Fort Hood, TX, for over a decade, and the BCV has also been studied at Fort Sill, OK, and Camp Bullis, TX (Rust and Tazik 1992; Grzybowski and Tazik 1993; Trame et al. 1997; Anders et al. 2000; Hayden et al. 2001; Jette et al. 1998; Tazik et al. 1992; Weinberg et al. 1998, Koloszar 1998; Koloszar and Bailey 1999; Koloszar and Bailey 2000; Cavanagh 2000; Boice 1998, Leyva et al. 2002). The ecology and life histories of both species on Fort Hood is summarized in the Fort Hood Endangered Species Management Plan (ESMP) (Hayden et al. 2001) and continued monitoring, as well as additional research specific to these species and their habitats, is ongoing at Fort Hood (The Nature Conservancy 1998; 1999; 2000a,b; 2001; 2002; 2003). Both bird species inhabit areas dominated by shin oak (*Quercus sinuata* var. *breviloba*), Texas oak (*Quercus buckley*), and Ashe juniper (*Juniperus ashei*), on the mesa tops and slopes of the Edwards Plateau limestone formation, which extends across the installation (Hayden et al. 2001).

Habitat description and critical habitat metrics

The nesting habitats of the species differ primarily in their stages of ecological succession. BCV nesting habitat consists of early-stage successional vegetation of an age between 5 and 25 to 30 years after disturbance by fire or other sources. BCV habitat is characterized by a dispersed patchwork of scrub oaks and Ashe juniper thickets or patches within a matrix of open grassland and bare soil or rock. As Graber (1961) noted, the height of these woody vegetation patches in typical BCV habitat is highly irregular, often forming a “woolly” textured landscape dotted with shrubby clumps or “mottes” when viewed from a height. On very broad (regional) scales, the BCV appears to avoid areas dominated by juniper, but it seems to have an affinity for juniper cover on the nesting habitat when overall vegetation cover is low (Grzybowski et al. 1994). During succession, the scrubby trees eventually grow and reproduce until they begin to fill the available space, both horizontally and vertically. As the cover of vegetation closes and the trees grow taller, the habitat becomes less suitable for BCV for nesting, but progressively more suitable for GCW nesting. Prime nesting habitat for the GCW consists of tall, dense, mature stands of Ashe juniper mixed with hardwoods such as plateau live oak, Texas red oak, shin oak, Texas ash, cedar elm, Arizona walnut, escarpment black cherry, and hackberry. Approximately 25 to 50 years after disturbance, the junipers begin to shed strips of bark, which the GCW requires to build its nest. After about 50 years of succession, the vegetation is fully mature GCW habitat (U.S. Fish and Wildlife Service 1991, 1992; Campbell 1995).

Remote sensing of key biophysical parameters is useful at multiple scales for both species. At a local scale, the most salient ecological characteristics of the species are the vegetation composition and structure, both within the territory and immediately surrounding the nest, territory, and nest-site location. At a landscape scale, the spatial pattern of individual vegetation patches containing one or more nest locations or territories may have some influence on habitat preference (Craft 1998; Dearborn and Sanchez 2001; Horne and Anders 2001; Leyva et al. 2003).

Each species requires a different set of metrics to define viable habitat. Assessment of warbler habitat requires an accurate characterization of the proportional mixture of evergreen (primarily Ashe juniper) and deciduous trees in mature forest stands. The height and variability of height of mature stands, and an assessment of canopy closure and gaps is also important for determining the age and maturity of the stands (Craft 1998; Dearborn and Sanchez 2001; Horne and Anders 2001; Leyva et al. 2003). Proximity to water is also important, but that can be easily determined using basic GIS capabilities. Assessment of vireo habitat requires the delineation of individual vegetation patches and metrics of vertical structure of these patches, particularly between 0 and 3m height, with vegetative type and composition being less critical (Cimprich 2002; Leyva et al. 2002).

Current limitations for assessing critical habitat metrics

Specific to assessing GCW habitat, some critical biophysical parameters that determine habitat suitability can be assessed by using already established protocols for automated image assessment and manual aerial photo interpretation. At Fort Hood, TX, existing mixed, relatively closed canopy, evergreen/deciduous stands are likely to be mature stands, and therefore are considered potential warbler habitat. Using a combination of aerial photo interpretation and field observations, a 2-category map of GCW habitat at Fort Hood (i.e., habitat and non-habitat) has been developed and is updated on a regular basis to reflect changes due to disturbance and natural succession (Horne and Anders 2001).

Although these habitat maps exist, there is still significant spatial variability with one or several biophysical parameters within areas designated as habitat. These biophysical parameters are critical to determining habitat suitability or preference within these “habitat” areas. Characterizing the spatial variability of such biophysical parameters is both labor-intensive and difficult, because it requires extensive field surveys and specialized air photo interpretation skills. Metrics derived from remotely-sensed imagery that identify habitat type or quantify spatial pattern and vertical structure have been difficult to incorporate into habitat characterization and monitoring protocols for GCW and BCV, as well as for many other TES, because of the limited spatial and spectral resolution of traditional passive sensor technology. Therefore, it is cost-prohibitive, and in many cases, not feasible to characterize all biophysical parameters that are critical for determining habitat suitability, particularly in inaccessible areas.

Determination of forested versus non-forested areas and the proportional composition of deciduous and evergreen vegetation within forested areas is relatively straightforward with large scale, multidate photography (leaf-on and leaf-off), or even single date large scale photography acquired at the appropriate time (Spurr 1948). The recent availability of higher spatial resolution satellite imagery ($\leq$ 5.0m) also provides an adequate data source for determining the proportional mixture of evergreen and deciduous tree species, although individual tree crowns may not be discernable at this smaller scale, and therefore estimates may be less accurate (Brandtberg 1998; Hill and Leckie 1999; Key et al. 2001).

It is possible to measure mean stand age directly from field core samples, or it can be estimated using height measurements (either measured in the field or estimated from imagery), stand composition, and a site index. It becomes increasingly more difficult to characterize the spatial variability in age within uneven aged stands. Accurate estimates of mean canopy height for a stand can be extracted from large-scale photography and stereo pairs of photographs using photogrammetric methods, although this requires that individual tree tops and bare ground be visible, which does not always occur (Spurr 1948). However, in addition to inefficiencies and inaccuracies associated with estimating height using photogrammetric methods, height is not a suitable surrogate measure of age for Ashe junipers (an integral component of GCW habitat). Mature juniper trees vary in age and growth form depending on many biotic and abiotic factors, including soils, moisture, aspect, slope, and historical land use. Trees that have shredding bark at least near the base are an essential element on the nesting territory for GCW, because the females uses this bark to construct the nest. Ashe junipers must be mature before their bark begins to shred (Ladd and Gass 1999). Therefore, variability of canopy height and canopy closure are more appropriate surrogate measures of stand age within mature, mixed stands of juniper and various hardwoods (Leyva et al. 2003). Similar to stand height, canopy closure can be estimated from large-scale photography either by ocular estimate or automated methods (Spurr 1948). Estimation of canopy closure becomes more difficult as stand closure increases because small openings are hard to detect and are sometimes obscured by shadows (Avery and Berlin 1985).

Additionally, in dense and relatively closed canopy forest and shrubland environments typical of habitat for many avian TES, remotely sensed data only provided some measure of the height and composition of the overlying canopy, with limited capabilities for sensing the vertical structure and density of sub-canopy, midstory, and understory habitat characteristics. Sub-canopy habitat characteristics can only be inferred from overstory parameters that can be measured with remotely sensed imagery (Stenback and Congalton 1990; Krause et al. 2001). Moderate resolution satellite imagery (10- to 30-m spatial resolution) has been used to estimate above ground biomass as a surrogate measure of canopy density at very coarse, regional scales (Avery and Berlin 1985; Sader et al. 1989; De Wulf et al. 1990; Fazakas et al. 1999). In addition to these passive optical sensors, active sensor technology such as radar that has some capability to penetrate the upper canopy has also been used to estimate biophysical parameters related to vertical structure (Ranson et al. 1997; Nezry et al. 1993; Harrell et al. 1995; Hyyppa and Hallikainen 1996; Hyyppa et al. 2000). However, errors associated with canopy height estimates derived from radar data are greater than the variability of canopy heights that must be assessed to evaluate habitat suitability (Toutin and Amaral 2000; Riano et al. 2003). In addition; optical sensors and radar will saturate at the high biomass levels associated with many dense, mature forest types, including suitable GCW habitat, and therefore are insensitive to spatial variability in above ground biomass, and indirectly, vertical structure of the canopy in many dense, mature forest types (Waring et al. 1995; Kasischke et al. 1997; Lefsky et al. 2002; Riano et al. 2003).

Specific to assessing BCV habitat, the limited capabilities of optical systems for sensing the vertical structure and density of sub-canopy, midstory, and understory habitat characteristics make it impossible for determining the vertical structure of woody shrub/scrub vegetation between 0 and 3m that is critical for determining BCV habitat suitability. Characterization of canopy height for small trees and shrubs using photogrammetric methods has also been especially difficult, and oftentimes, inaccurate (Ritchie et al. 1992; Weltz et al. 1994; Naesset and Bjerknes 2001). Field inventories of this habitat type are labor intensive and costly, and due to the costs, many smaller shrub/scrub vegetation patches are simply not inventoried (Craft 1998; Koloszar and Horne 2000; Leyva et al. 2002; Cimprich 2002).

Emerging technologies to address limitations

An emerging remote sensing technology referred to as airborne laser scanning (ALS) or airborne light detection and ranging (LIDAR) shows great promise for sensing some upper canopy parameters in a more efficient and cost-effective manner and more importantly, for assessing sub-canopy vertical structure, which previously could not be assessed remotely. Airborne LIDAR systems transmit laser pulses towards the ground and then determine the distance to the target based on the time required for the laser pulse to return to the sensor. In forested environments, the laser pulses are intercepted by various targets, including vegetation at varying levels within the forest canopy, and bare ground. For each return, a precise location and elevation is determined. Using only those returns intercepted by bare ground, a very detailed and accurate digital elevation model of bare earth can be produced, even in areas of dense canopy. Using the bare earth DEM as a baseline, a detailed and accurate measurement of the height of the remaining non-ground returns can be determined. The spatial resolution is sufficient to examine characteristics of individual trees. LIDAR data has been used to accurately measure or estimate a large number of forest stand characteristics, including tree height (Nelson et al. 1988; Drake and Weishampel 2000; Brandtberg et al. 2003; Popescu and Wynne 2004), diameter (Hyyppa et al. 2001; Lefsky et al. 2001), tree crown properties (Magnussen and Boudewyn 1998; Naesset and Okland 2002; Persson et al. 2002), canopy gaps and closure (Lefksy et al. 2002; Holmgren et al. 2003a.) and stand density and volume (Maclean and Krabil 1986; Nilsson 1996; Naesset 1997; Lefsky et al. 1999a; Lefsky et al. 1999b; Holmgren et al. 2003b). LIDAR has also been used specifically to assess forest structure as it relates to habitat preference (Hinsley et al. 2002; Leyva et al. 2002; Hill et al. 2003; Mason et al. 2003).

In addition to the possibility of sensing biophysical parameters that are critical to determining habitat suitability for GCW, LIDAR may have even greater potential for determining the vertical structure of woody shrub/scrub vegetation between 0 and 3m that is critical for determining BCV habitat suitability (Ritchie et al. 1992; Weltz et al. 1994; Naesset and Bjerknes 2001). Assessment of the height and vertical structure in woody shrub/scrub vegetation patches would address a significant information gap with respect to determining habitat suitability for BCV.

Red-cockaded Woodpecker

Background

The federally endangered red-cockaded woodpecker (*Picoides borealis*) is a small bird native to open, mature and old growth pine ecosystems in the southeastern United States. A recovery plan is in place that provides a detailed description of the historical range, life history, ecology, and preferred habitat for this cooperative breeding species (U.S. Fish and Wildlife Service 2003). The RCW is found on 11 military installations in the southeastern United States, and in 1994, the Army established Army-wide management guidelines for the species (Carter and Hayden 1994; Hayden 1994). The species continues to be studied and managed intensively on both military and other lands (Conner and Rudolf 1991a; Costa 1997; James 1991, James et al. 1997, 2001; Walters et al. 1998, 2000; Balbach and Kirby 2001).

Habitat description and critical habitat metrics

Red-cockaded woodpeckers inhabit areas dominated by large, older pines with lower densities of small and medium pines, sparse or minimal hardwood midstory, and bunchgrass or forb groundcover. Large, older pines are required for cavity trees. The cavities are excavated within inactive heartwood in these older trees so that the cavity interior is resin-free. Completed cavities in active use have numerous, small resin wells that exude sap. The birds keep the sap flowing as a cavity defense mechanism against snakes and other predators. Heartwood decay also facilitates the excavation process. Mature longleaf pines (*Pinus palustris*) are preferred over loblolly (*Pinus taeda*), shortleaf (*Pinus echnata*), and other southern pine species for nesting. Herbaceous groundcover is required to sustain fire, which is necessary to minimize midstory hardwood encroachment (Ligon et al. 1986; Costa and Escano 1989; Conner and Rudolph 1991b; James 1991; U.S. Fish and Wildlife Service 2003).

Assessment of RCW nesting and foraging habitat requires an accurate assessment of key biophysical parameters, including stem density and basal area by size class for pines (preferably by pine species), assessment of the presence and density of midstory hardwoods, and the presence of preferred herbaceous groundcover.

Current limitations for assessing critical habitat metrics

As discussed earlier, manual interpretation of aerial photography and photogrammetric methods can be used to estimate mean height and stem density for forest stands, but these methods require specialized expertise and are labor intensive, costly, and inconsistent. One additional forest structure parameter that is critical to determining habitat suitability for RCW is the existence and density of midstory hardwoods. Characterization of midstory hardwood density has not been possible with passive sensor technology. In addition, it has also been difficult to distinguish between preferred longleaf pine species and off-site loblolly and shortleaf pines. Historically, longleaf pines have been preferred host trees for nest cavities due to their longevity and associated larger size relative to other pine species. Although preferred pine species composition in preferred habitat may not be fully understood, monoculture stands of longleaf pine, or stands with some longleaf pine composition are more desirable that stands containing no longleaf pine. Characterization of pine species composition with remote sensing has been difficult because of the spectral ambiguity of these species (Wulder 1998). Limited spatial resolution also results in a mixed spectral signature for individual pixels, which may include a combination of multiple pine species, hardwoods, and groundcover.

Emerging technologies to address limitations

Automated methods for extracting forest inventory parameters have been developed that are improving both the efficiency and accuracy of basal area estimates (Leckie 1990; Wulder 1998). Advancements in the spatial and spectral resolution of remote sensor platforms now provide the capability to delineate individual tree crowns for improved estimates of forest stand structure. Automated methods have been developed to delineate individual tree crowns from high spatial resolution multispectral imagery (Gougeon 1995a,b; Wulder et al. 2000; Key et al. 2001; Pouliot et al. 2002) and to delineate individual tree crowns and measure individual tree height with

LIDAR (Wulder et al. 2000; Hyyppa et al. 2001; Persson et al. 2002; Brandtberg et al. 2003; Popescu et al. 2003). Methods have also been developed to fuse information from multispectral and LIDAR data for delineating individual tree crowns and estimating tree height (Leckie et al. 2003; McCombs et al. 2003; Popescu and Wynne 2004). Such advancements in sensor technology, particularly LIDAR, and automated analysis of high spatial resolution multispectral imagery and LIDAR should greatly improve the efficiency and accuracy of estimating basal area of pines by different size classes, which is critical to assessment of RCW habitat.

LIDAR data provides some measurement of the entire vertical distribution of the forest canopy, and therefore, is also a promising technology for assessing the presence and density of midstory hardwoods (Lefsky et al. 2002; Riano et al. 2003).

Hyperspectral data may have some potential for distinguishing between these pine species, as it provides a larger number of more narrow spectral bands in comparison to traditional multispectral imagery. Distinct reflectance and absorption characteristics of different pine species may be detectable within one or several narrow spectral bands that would allow for automated identification of species type.

Desert Tortoise

Background

The desert tortoise (*Gopherus agassizii*) is a terrestrial tortoise that inhabits the deserts of the southwestern United States, with a historical range of the Mojave and Sonoran deserts of southeastern California, southern Nevada, southwestern Utah, and western Arizona. The entire Mojave population was federally listed as threatened on 2 April 1990 (Fish and Wildlife Service 1990). The Mojave population is defined as the tortoises occurring north and west of the Colorado River (U.S. Fish and Wildlife Service 1994). A recovery plan is in place that provides a detailed description of the historical range, life history, ecology, and preferred habitat for the species (U.S. Fish and Wildlife Service 1994). Within the Western Mojave Recovery Unit, desert tortoises exist on all major DoD installations, and therefore, significant research has been focused on management of the species and its habitat on DoD lands (Krzysik and Woodman 1994; Krzysik 1994a,b; Duda et al. 1999; Tazik and Martin 2002).

Habitat description and critical habitat metrics

Desert tortoises occupy a wide variety of habitats in the United States, including a broad range of landforms and soil types (Ernst et al. 1994). The Mojave population of the desert tortoise is found primarily on flats and bajadas characterized by scattered shrubs and abundant inter-space for growth of herbaceous plants, with soils ranging from sand to sandy-gravel. Desert tortoises are also found on rocky terrain and slopes, and there is significant geographic variation in the way desert tortoises use available resources. They generally occur below the 1250-m elevation in creosote bush and saltbush scrub habitats (Berry and Turner 1986; Barrett 1990; Bury et al. 1994; Germano et al. 1994; U.S. Fish and Wildlife Service 1994). They require soils that are conducive to digging burrows. Soil friability, or its tendency to break apart, has been cited as an indicator of tortoise habitat. The tortoise must have suitable soils and terrain for constructing a burrow and must have adequate annual and perennial plants in the spring and/or summer for forage (Brooks 1997; Nagy et al. 1998).

Current limitations for assessing critical habitat metrics

Descriptions of preferred habitat for the species are broad and general. Geospatial technologies have been used to link presence and density of tortoises with a large number of potential habitat characteristics, including slope and aspect, soil composition, parent materials, plant cover, elevation, winter precipitation, microtopographic variability, and soil friability (Weinstein 1989; Westervelt et al. 1997; Andersen et al. 2000). There has been very limited application of remote sensing technologies to characterization of their habitats because detailed and specific preferred habitat characteristics are still relatively unknown. In addition, many of the habitat characteristics of the species cannot be adequately characterized from remote observations, at least not at an appropriate scale for habitat characterization. Furthermore, observation of burrow entrances is difficult using vertical aerial photographs because of their relatively small size, the angle of the entrance relative to the instantaneous field of view of the sensor, and the view can be blocked by nearby shrubs.

The availability of imagery with high spatial and spectral resolution has improved the ability to map desert scrub vegetation, but arid vegetative cover is typically sparse, resulting in a mixture of vegetation and bare ground spectra within individual pixels. Therefore, mapping of desert vegetation, especially spring and summer annuals used by tortoises for forage, remains complex and difficult (Ray and Murray 1996; Driscoll et al. 1997; Hunt et al. 2003). In addition, the limited spatial and spectral resolution of traditional passive sensor technology does not provide a means for developing a DEM at the necessary micro scale of an individual burrow location.

Emerging technologies to address limitations

LIDAR technology now provides the capability to characterize micro-topographic relief, and therefore provides a mechanism to further explore the relationship between burrow locations and micro-topographic relief. Radar technology may also provide some limited capability for assessing soil compaction and friability. However, the lack of specificity in description of preferred habitat for the species is still the primary limitation of assessing habitat suitability with remote sensing.

Gopher Tortoise

Background

The gopher tortoise (*Gopherus polyphemus*) is a terrestrial tortoise found in the southeastern United States and is the only tortoise indigenous to this region. The species is found in the sandy coastal plain areas from extreme southern South Carolina to the southeastern corner of Louisiana (Auffenberg and Franz 1982; Diemer 1986; U.S. Fish and Wildlife Service 1990b). The western population was listed as endangered in 1987. The western population is defined as those tortoises that lie west of the Tombigbee and Mobile Rivers in Alabama, across southern Mississippi and in extreme southeastern Louisiana. A recovery plan is in place that provides a detailed description of the historical range, life history, ecology, and preferred habitat for the species (U.S. Fish and Wildlife Service 1990b). Gopher tortoises are found on a number of DoD installations in the southeastern United States (Balbach et al. 1994; Schreiber et al. 1997).

Habitat description and critical habitat metrics

Gopher tortoise habitat is found in a variety of upland areas and can be characterized by the presence of well-drained, sandy soils for burrowing, an abundance of herbaceous ground cover and a generally open canopy with sparse shrub cover. The open canopy provides sunlit areas for nesting and thermoregulation, and also provides the necessary sunlight for the growth of abundant herbaceous ground cover. Although it is typically found in xeric, open pine woodlands, tortoises have been located in other vegetative communities where the physical characteristics described above are present. Regular burning helps maintain habitat for the species, and management for RCW habitat is generally also desirable for the gopher tortoise (Auffenberg and Iverson 1979; Diemer 1986; Stewart et al. 1993; U.S. Fish and Wildlife Service 1990b).

Current limitations for assessing critical habitat metrics

Similar to problems associated with remote sensing of desert tortoise burrows, some gopher tortoise burrows are difficult to locate and census during field investigations because their burrow entrances are small (especially for juveniles), or they are obscured by vegetation near the burrow entrance. Detection of burrows using remote sensing technology is not possible. Remote sensing does have some utility for characterizing key physical characteristics of the habitat. As described previously, canopy closure can be estimated from large-scale photography either by ocular estimate or automated methods, but becomes more difficult as stand closure increases because small openings are hard to detect and are sometimes obscured by shadows (Spurr 1948; Avery and Berlin 1985).

In addition, micro-topographic relief is an important factor in identifying preferred well-drained, sandy soils in the southeastern coastal plain. The same limitations that apply to the desert tortoise also apply to the gopher tortoise in that the limited spatial and spectral resolution of traditional passive sensor technology does not provide a means for developing a DEM at the necessary micro scale surrounding burrow locations.

Emerging technologies to address limitations

The increasing availability of high spatial resolution imagery, as well as advancements in the analysis of LIDAR imagery provide more efficient methods for characterizing canopy closure (Wulder 1998; Leckie1990; Lefksy et al. 2002; Holmgren et al. 2003a).

LIDAR technology also provides the potential to develop a DEM that accurately characterizes the micro-topographic relief of bare earth surfaces, even in areas of significant vegetation and canopy cover. An accurate characterization of micro-topographic relief would allow for the identification of small, isolated patches of well-drained soils that would not be delineated on current soil maps because the size of the patches are smaller than the minimum mapping unit of the soil map.

Indiana Bat and Gray Bat

Background

The medium-size Indiana bat (*Myotis sodalis*) and slightly larger gray bat (*Myotis grisescens*) are both endangered throughout their respective ranges. The distribution of the Indiana bat is associated with limestone caves in the eastern United

States, but it is found across a large range spanning from New England to the Florida panhandle, and to the western edge of the Ozark region in Oklahoma. Most of the population occupies winter hibernacula in Indiana, Kentucky, and Missouri (U.S. Fish and Wildlife Service 1983). The gray bat is found primarily in Alabama, Arkansas, Kentucky, Missouri, and Tennessee, but is also found in Florida, Georgia, Kansas, Indiana, Illinois, Oklahoma, Mississippi, and Virginia (U.S. Fish and Wildlife Service 1982).

In a summary of threatened and endangered species presence on Army installations, Rubinoff et al. (2004) suggest that Indiana bat and gray bat occur on 8 and 7 installations, respectively. However, the data used in their summary do not include all Army installations or sites where Army training may occur. An alternative assessment, based on county-level distribution data from the species' recovery plans, suggests they are likely to occur on a great many more military installations (Shapiro and Hohmann, in prep).

Habitat description and critical habitat metrics

The habitat requirements for both species are seasonal. The Indiana bat roosts in trees during the summer, and hibernates in caves and mines during the winter. Summer foraging habitat consists of wooded, riparian areas, and nesting often occurs in dead trees and snags in sunlit areas. Males roost primarily in dead trees on upper slopes and ridge tops near their hibernaculum (Twente 1955; Garner and Gardner 1992; Humphrey et al. 1997; Humphrey 1978). Gray bats are found in cave like habitats year round and migrate between winter and summer caves (Barbour and Davis 1969; Tuttle 1976, 1979).

Current limitations for assessing critical habitat metrics

Although summer habitat for the Indiana bat has been broadly described as riparian hardwood forest, Menzel et al. (2001) provides an excellent overview of several biophysical parameters that have been linked to habitat preference from observational studies, including roosting tree type, condition, and structure; canopy cover; stem density; stand composition and structure; landscape variables; and juxtaposition with respect to water. However, minimal quantitative studies have been published, and those that have been published are site specific, and therefore cannot be used to determine habitat preference across the broad geographic range of the species. General descriptions of forest cover around cave entrances and forest cover along corridors between roosting and foraging areas for the gray bat are available, but a concise description of preferred gray bat habitat is also lacking (U.S. Fish and Wildlife Service 1982; Mitchell 1988).

Due to the lack of specificity in describing the individual biophysical characteristics of the preferred habitat for both bat species, the use of remote sensing to characterize the habitats of both species has not been reported in the literature. Additional research is required to adequately describe and quantify their preferred habitats, although remote sensing technology does have great potential for describing forest stand attributes that may be critical for determining habitat preference.

4 Summary

Ultimately, the two primary factors for determining the utility of remote sensing for characterizing habitats on military lands are: (1) the degree by which habitat characteristics are well-understood for a given species and (2) the applicability of remote sensing techniques to characterization of one or more biophysical attributes of such habitats. Considerable resources have been devoted to research related to conservation and preservation of these species by DoD, other state and federal agencies, and private organizations. As a result, the general habitat requirements for many critical species are well understood, although considerably more research has been focused on the three bird species and the two tortoise species, and considerably less on the two bat species emphasized in this report. Even for those species for which we have a general understanding of the habitat requirements, there are still information gaps associated with some key biophysical parameters that determine habitat suitability.

For all critical species, there is minimal published literature describing the specific use of remote sensing to characterize their habitats. However, remotely sensed imagery has been used to characterize many of the individual biophysical parameters that partially determine suitability of habitat for these species, and in particular for the three bird species. Remote sensing technologies have been used less frequently for assessing biophysical parameters related to tortoise habitat preference, and have not been used to assess the habitats of bats, partially because their habitat requirements are more broad and diverse, and partially because there is a less developed understanding of their habitat requirements.

The primary information gaps associated with critical biophysical parameters of preferred habitat for Army critical species appear to be related to forest structural characteristics, especially for the avian species. Although photogrammetric methods have been a long established method for characterizing many forest stand attributes that are critical to TES characterization, LIDAR is becoming increasingly cost-effective and a more efficient means for collecting such information (Baltsavias 1999; Lefsky et al. 2002). The emergence of high spatial and spectral resolution imagery, as well as LIDAR, provides the ability to delineate and assess individual tree properties as opposed to locally averaged stand parameters (Wulder 1998; Brandtberg et al. 2003). In addition, LIDAR provides information related to the vertical organization of the forest canopy. As these technologies become more cost-effective, assessment of forest characteristics at this scale shows great promise for assessing individual biophysical parameters that determine habitat preference for many endangered species, including those critical to the DoD.

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14. ABSTRACT

The presence of federally listed threatened and endangered species (TES) and their habitats on Department of Defense (DoD) lands has a significant impact on current and future training and testing mission activities. To meet the requirements of the Endangered Species Act, the DoD requires accurate, cost-effective surveying and monitoring methods to characterize and monitor the habitats of TES on military training and testing lands.

Remotely sensed imagery provides an ideal supplement, or surrogate, to field surveys and has the potential to greatly enhance the speed, accuracy, and economy of TES habitat assessments. This report provides a general overview of rele-vant literature describing the best available science and protocols currently implemented to characterize and monitor habitat for TES, with a particular emphasis on the seven high priority species of the DoD: Indiana bat (*Myotis sodalis*), gray bat (*Myotis grisescens*), gopher tortoise (*Gopherus polyphemus*), desert tortoise (*Gopherus agassizii*), red-cockaded woodpecker (*Picoides borealis*), black-capped vireo (*Vireo atricapillus*), and the golden-cheeked warbler (*Dendroica chrysoparia*).

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